THALis: A Topology-Preserving Brain-Computer Interface for Dexterous Non-Invasive EEG-Driven Hand Control

Bhatt, Krishna (School: BASIS Independent Silicon Valley)

Over 80 million people face loss of upper-limb function. Yet noninvasive electroencephalogram (EEG) prosthetic hand interfaces are limited to cumbersome, binary control due to severe signal noise—often 90% greater than invasive counterparts. Deep convolutional methods struggle in this noisy, data-scarce setting, leaving a major gap in our current capability. To address this, I developed THALis, the first noninvasive system to our knowledge to proportionally decode multi-finger motion from scalp EEG alone. My core innovation reframes neural decoding as a dynamical reconstruction problem: THALis acts as a state-observer replicating subject-specific brain dynamics for prosthetic inference, bypassing noise as a structural bottleneck. I achieve this via a novel theory-driven approach: (1) Via Takens embeddings, I show latent cortical mappings for finger control are recoverable from EEG-scale observations while preserving homotopy under bounded noise. (2) I exploit this to design an echo-state reservoir with a bifurcation mechanism generating attractors topologically conjugate to cortical limit cycles. (3) A phase-locked-loop decodes proportional finger position from the reservoir, reducing a nonlinear problem to a tractable linear one. On cross-validated consumer EEG tests, THALis tracks realtime finger kinematics at $r=0.68\pm0.04$—a 54.5% improvement over state-of-the-art CNNs—while achieving 81.78% 4-primitive accuracy. The reservoir preserves distinct representations (Cohen's $d=1.19$) with 10-minute calibration. By decoupling decoder integrity from signal quality, THALis proposes a scalable nonsurgical path to natural control. My approach can extend to motor disease monitoring and multimodal neuroanalysis, warranting further study as a general foundation for noninvasive BCI.

Awards Won:

Third Award of $1,200